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Observation of Electron Beam Plasma Instability between Two Mesh Boundaries

By
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Abstract: An unstable oscillation is observed to be excited in the Pierce electron beam plasma system between boundaries. The instability appeared between two mesh electrodes is controlled by parameters such as the plasma density and the mesh bias voltage relating to the plasma frequency and the electron beam energy, respectively. The system becomes chaotic when the oscillation is slightly out of the resonance condition of the Pierce instability.

Key words: electron beam plasma system, boundary, Pierce instability, unstable oscillation, resonance condition, chaotic behavior

1. Introduction

Bifurcation phenomena and chaotic state in plasma have been investigated. The bifurcation phenomena were originated from chaotic phenomena concerning the nonlinearity of plasma sheath (1) or the instability of discharge (2-6) that have been observed in many experiments. Recently, the chaotic phenomena such as period doubling (7,8), intermittency (9) and quasi-periodic chaos originated from unstable waves in plasma have been found. The above nonlinear phenomena were observed in the infinite plasma without boundary condition. On the other hand, the system tends to become linear state in the plasma with boundary and nonlinear phenomena would be difficult to produce even with large amplitude. Therefore, the bifurcation phenomena between boundaries in plasma have hardly been observed.

When an electron beam plasma system is formed in the plasma between boundaries, the Pierce instability is generated (10). The chaotic dynamics of the Pierce beam plasma system including warm plasma effects has been studied using computer simulations (11). Also, the chaotic phenomena in the extended Pierce beam plasma system have been calculated varying the potential structure between boundaries (12).

We have found the chaotic phenomena in an electron beam plasma system that is due to nonlinearity of unstable plasma waves (13,14). In this paper, we report the experimental results on the bifurcation phenomena in the Pierce electron beam plasma system produced between boundaries.

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2. Experimental Apparatus

A schematic diagram of the experimental apparatus is illustrated in Fig. 1. Dimensions of the chamber were 800 mm in axial length and 300 mm in diameter. The chamber was evacuated to 10^{-4} Pa, then argon gases were introduced into the chamber with the pressure of 5×10^{-2} Pa. Unmagnetized plasma was produced by the electron emission from two heated tungsten wires (length = 100 mm, diameter = 0.23 mm). Typical plasma parameters in the experimental region are as follows: the electron density $n_e = 10^8$ cm^{-3} and the electron temperature T_e = 1 eV, which were nearly constant throughout the experiment.

Two mesh electrodes made of stainless steal (50 line/mesh) with the diameter of 80 mm were fixed coaxially at the center of the chamber as shown in Fig. 1. The electrodes were set at parallel with the distance of 5 cm.

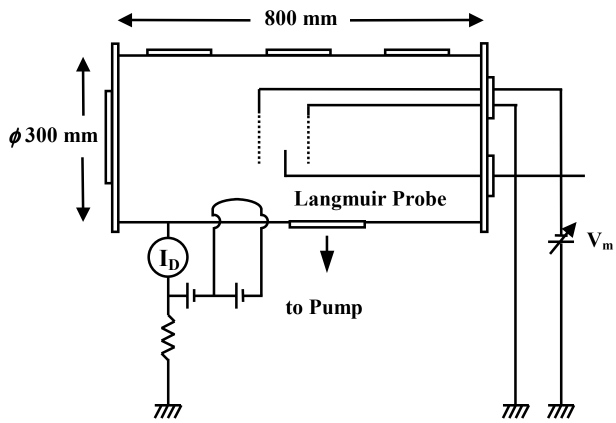

Fig. 1. Schematic diagram of the experimental apparatus.

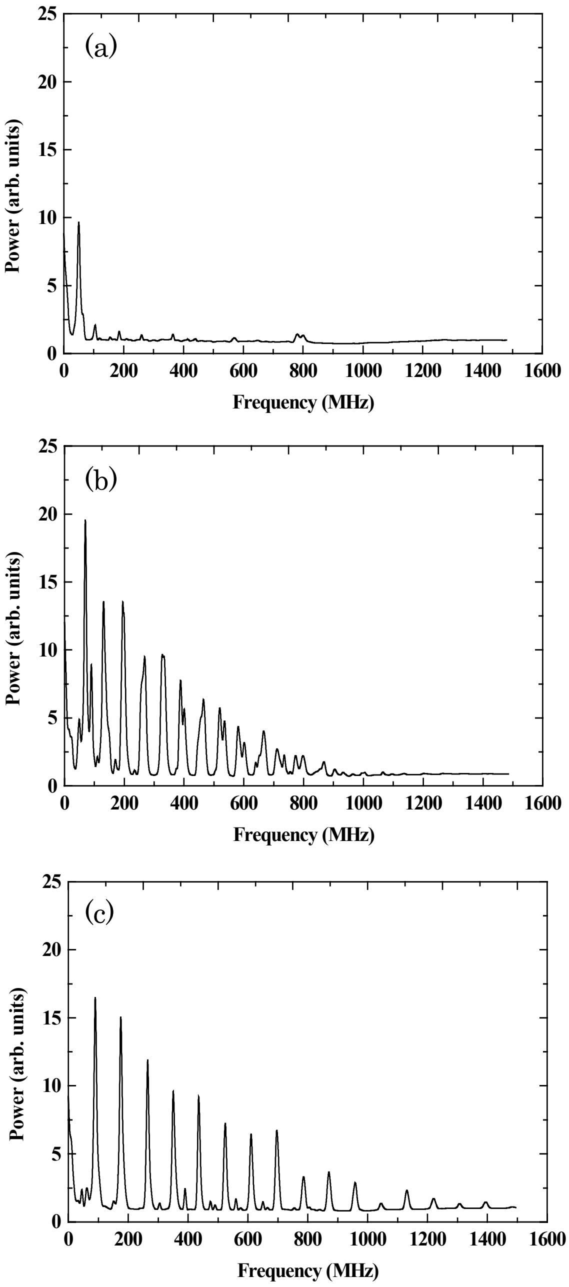

Fig. 2. Typical frequency spectra varying the discharge current I_T.

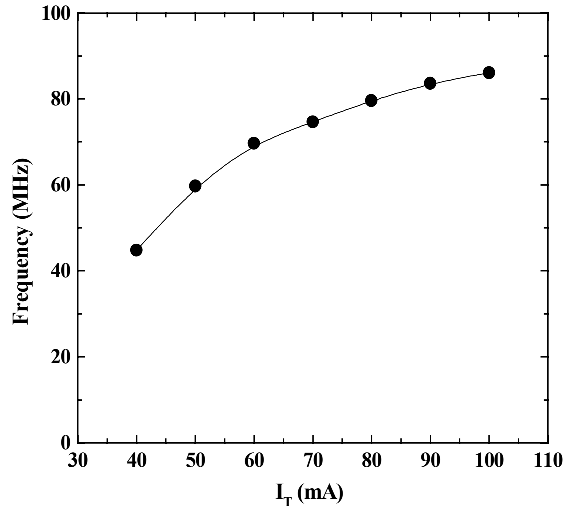

Fig. 3. Dependency of the frequency of fundamental wave on the discharge current.

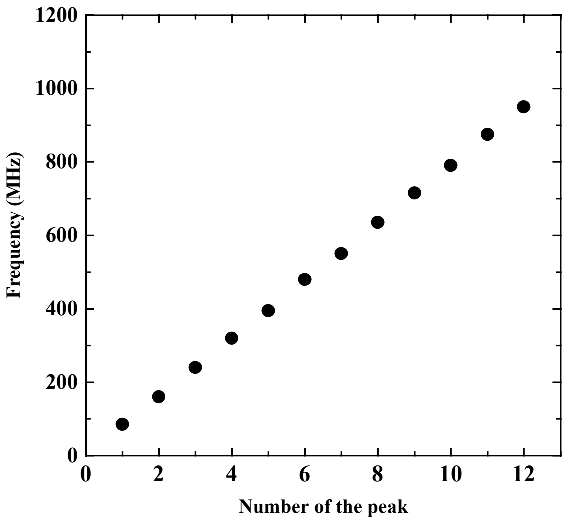

Fig. 4. The frequency of each peak in the frequency spectrum.

One of the mesh electrodes was biased negatively (V_m = 40～60 V) and the other was grounded. This system is called extended Pierce electron beam plasma system [12]. Electrons were accelerated by the potential difference, which was formed between the two mesh electrodes, and the electron beam was produced. The energy of the electron beam, which was proportional to the potential difference, is controlled by the mesh bias voltage V_m.

Plasma parameters and wave signals between the electrodes were measured with a cylindrical Langmuir probe (L = 2 mm, diameter = 0.3 mm). The frequency spectra were obtained from the observed wave signals of the floating potential of the Langmuir probe using a spectrum analyzer. The time series of the perturbation component of the floating potential were stored to a digital oscilloscope and analyzed by a computer.

3. Results and Discussion

3.1 Instability in boundaries

The unstable oscillation was observed to be excited in an electron beam plasma system between boundaries. When the discharge current I_T that corresponds to an electron density ne in the experimental region is small, 40 mA, the fundamental oscillation around 50 MHz was excited spontaneously, as shown in Figs. 2. The higher harmonics of the fundamental wave were found to be generated up to 1GHz at I_T = 60 mA. In this case, the peak width of the fundamental wave and higher harmonics was relatively broad, and the fine structures appeared on the peaks. When I_T was increased to 100 mA, the amplitudes of the peaks became large and the peak width became small. Fine structures on the peaks disappeared. The system seems to be regular state at I_T = 100 mA and on the resonance condition of the Pierce instability described later.

We investigated the mode of fundamental wave. The dependency of the frequency of the fundamental oscillation on electron density is illustrated in Fig. 3. The each frequency almost agrees with the electron plasma frequency f_{pe}, and the dependency on the electron density is similar with the electron plasma wave. Therefore, the fundamental wave belongs to the Langmuir mode of the electron beam plasma system.

Figure 4 shows the frequencies of each peak obtained from the frequency spectra. Since the interval between each peak is constant unlike the ion acoustic instability [9], observed oscillation is confirmed to be higher harmonics of the electron beam plasma instability between boundaries. However, the excitation mechanism of the higher harmonics has not been clarified. Figures 5 indicate the typical frequency spectra without and with the boundaries of mesh electrodes described above. In the case of infinite plasma without boundaries, only a single oscillation is excited spontaneously with the frequency of approximately f_{pe}. The higher harmonics are excited when the boundaries of mesh electrodes are immersed in the plasma. Therefore, the observed bifurcation phenomena are confirmed to originate from the instability between boundaries.

Figure 6 illustrates the dispersion relations of observed fundamental wave and higher harmonics (closed circles), and theoretical dispersion relation of the Pierce instability (opened circles). The solid lines denote the theoretical dispersion relation of the electron beam plasma system of infinite space. The dispersion relation of observed fundamental wave and higher harmonics were measured at the regular state of the frequency spectrum, where I_T = 80 mA and V_m = 40 V. The dispersion relation of the Pierce instability using the fluid theory is written as follows [10],

$$\frac{\omega^2}{\omega^2-\omega_{pe}^2}+\frac{i\omega_{pe}^2}{2\alpha}\left(\frac{e^{i\alpha(\omega-\omega_{pe})/\omega_{pe}-1}}{(\omega-\omega_{pe})^2}-\frac{e^{i\alpha(\omega+\omega_{pe})/\omega_{pe}-1}}{(\omega+\omega_{pe})^2}\right)=0$$

$$(\omega-kv_0)^2=\omega_{pe}^2$$

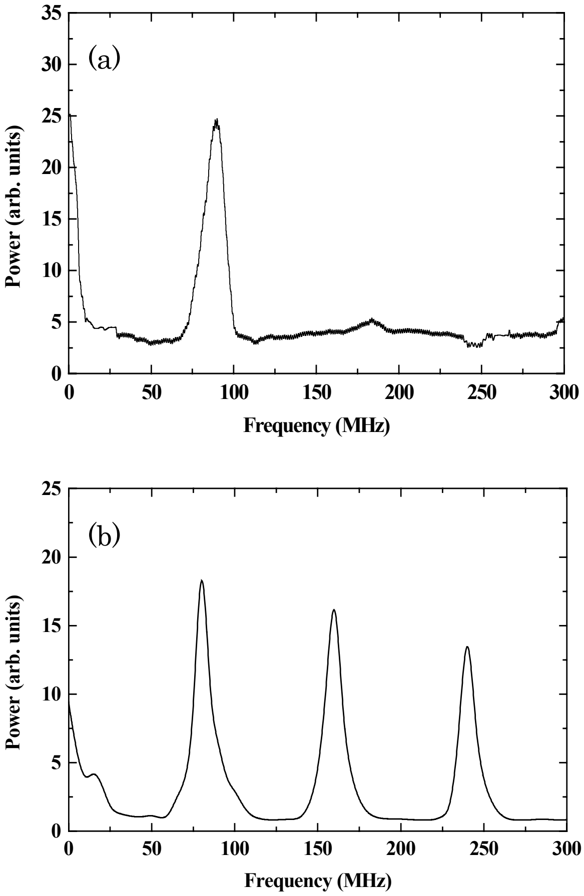

Fig. 5. Typical frequency spectra without (a) and with (b) the boundaries of mesh electrodes.

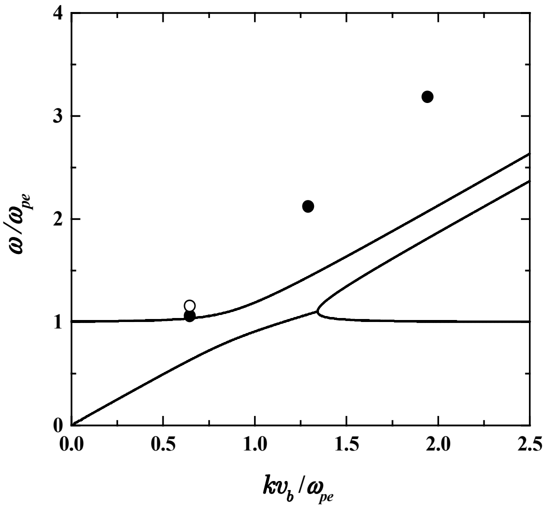

Fig. 6. Dispersion relations of the observed instability (closed circle) and the Pierce instability (opened circle). The solid line indicates the theoretical dispersion relation of the electron beam plasma system.

where, bulk plasma and electron beam are assumed to be cold ($v_{the} = v_{thb} = 0$), and α is,

$$\alpha = \frac{L}{v_0}\omega_{pe} \quad ,$$

where v_0 is the initial velocity of the electron beam from an electrode to plasma, L is a distance between mesh electrodes. The resonance condition of the Pierce instability is $\alpha = n\pi$, that is,

$$f_{pe} = \frac{n}{2}\frac{v_0}{L} \quad .$$

The observed fundamental wave agree with the dispersion relation of the Langmuir mode of an electron beam plasma system in the infinite space. While, the higher harmonics do not satisfy the dispersion relation. This situation is similar to the nonlinear Schrödinger equation.

The mesh bias voltage V_m relates to the electron beam energy in the experimental region. When V_m was small (0～30 V) only the fundamental unstable waves was excited. The fundamental wave and its higher harmonics appeared at V_m = 40 V, as shown in Fig. 7(a). The narrow and sharp profile of the peaks on the spectra indicates that the system is regular state. The electrons are accelerated to the velocity v_0 by the V_m and the distance between electrodes L is constant, 5 cm. The f_{pe} is 75 MHz in this case, V_m = 40 V. Then, from the resonance condition eq.(4), n is approximately 2, integer. Therefore, the system is on the resonance state of the pierce instability satisfying the boundary condition.

When Vm was increased to 50 V the spectrum became broad profile, as shown in Fig. 7(b). In this case, the n number of eq.(4) is estimated to be 1.8 and the system is slightly out of resonance state. The broaden peak of the spectrum imply that the system become turbulent or chaotic. At V_m = 60 V, the system is completely out of resonance state and the boundary condition is no longer effective. The n number of eq.(4) is 1.6. Then only the fundamental peak is significant in the spectrum of Fig. 7(c). Therefore, V_m is the control parameter of the system's behavior.

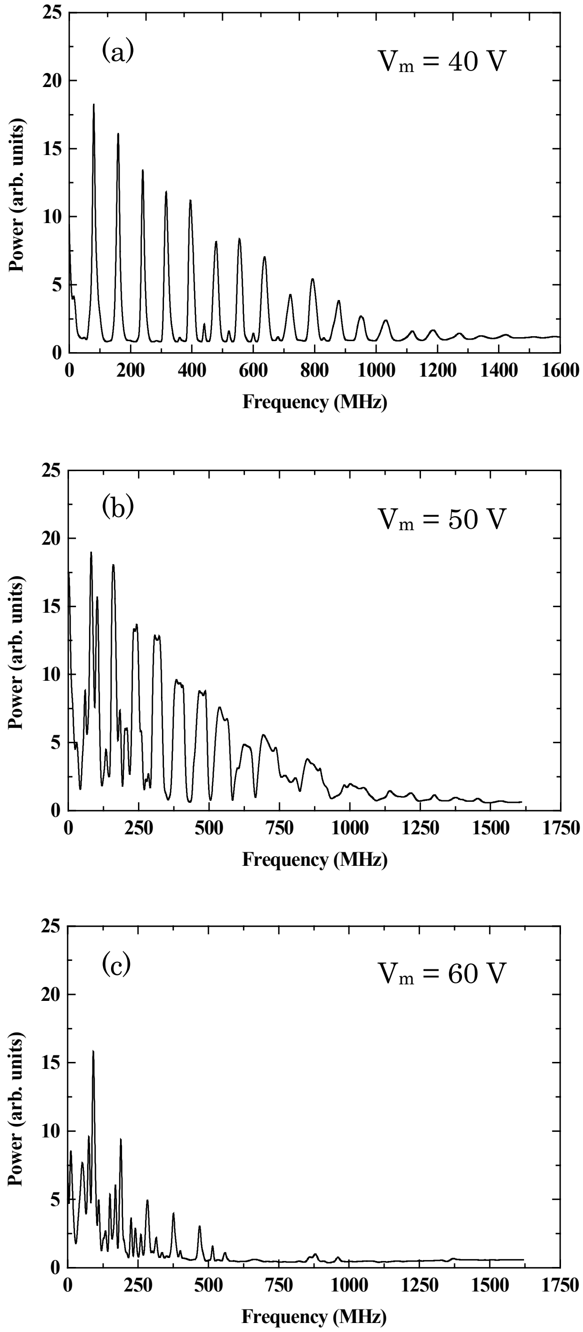

Fig. 7. Typical frequency spectra varying the mesh bias voltage Vm from 40 V to 60 V.

3.2 Behavior of the system

The behavior of the system is investigated changing the mesh bias voltage V_m, that is, the resonance parameter α, in order to determine whether the system became chaotic or not. Figure 8 (a) shows the time series of fluctuation component of the floating potential of a Langmuir probe at V_m = 40 V. The waveform indicates the periodic or quasi-periodic state. The phase space attractor is reconstructed from the time series with the data point of 16,000 using the embedding method [15,16]. As shown in Fig. 8(b), the torus type attractor appeared in the three-dimensional phase space. The correlation dimension of the attractor is calculated using the method of Grassberger and Procaccia [17]. The correlation dimension D is integer, 2.0, as indicated in Fig. 8(c). Then the system is confirmed to be the periodic or quasi-periodic state. When V_m increased from 40 V to 50V, the system would be out of the resonance slightly and becomes irregular state.

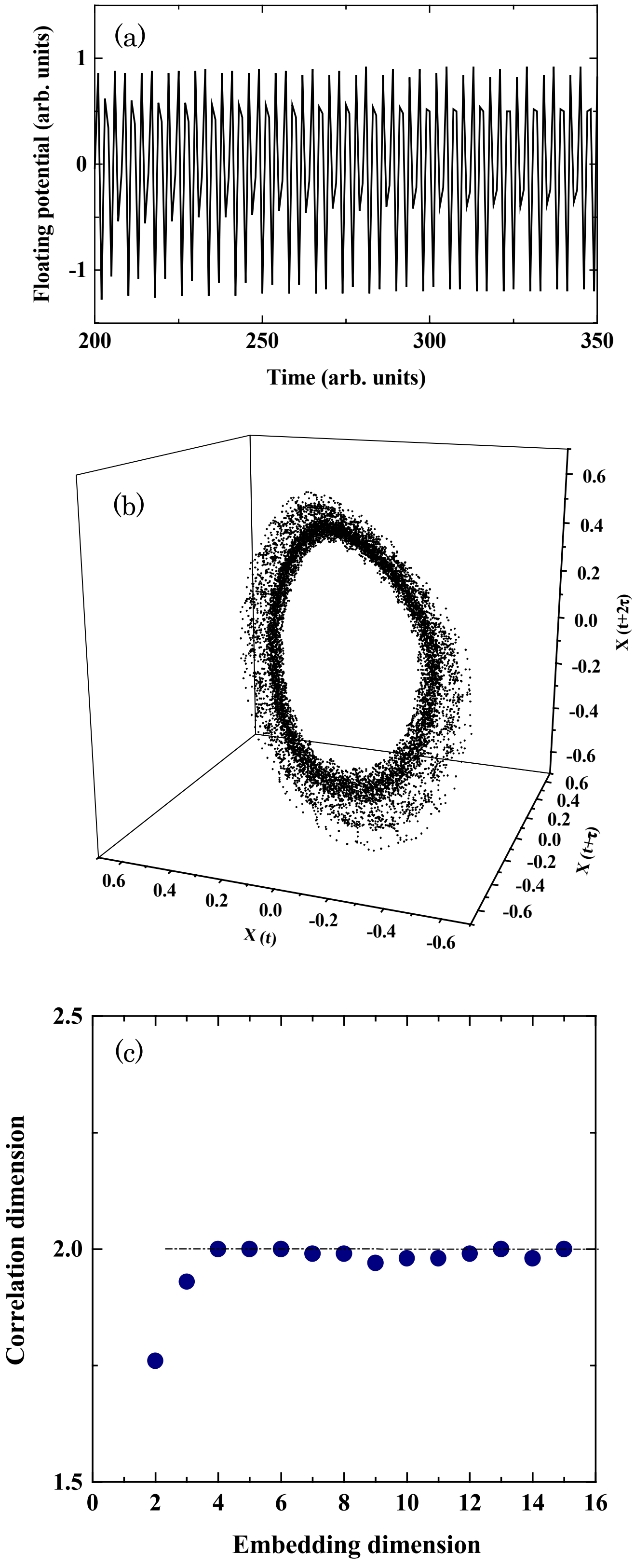

Fig. 8. Time series of floating potential, attractor of the system, and correlation dimension of the attractor of the periodic state shown in Fig. 7(a).

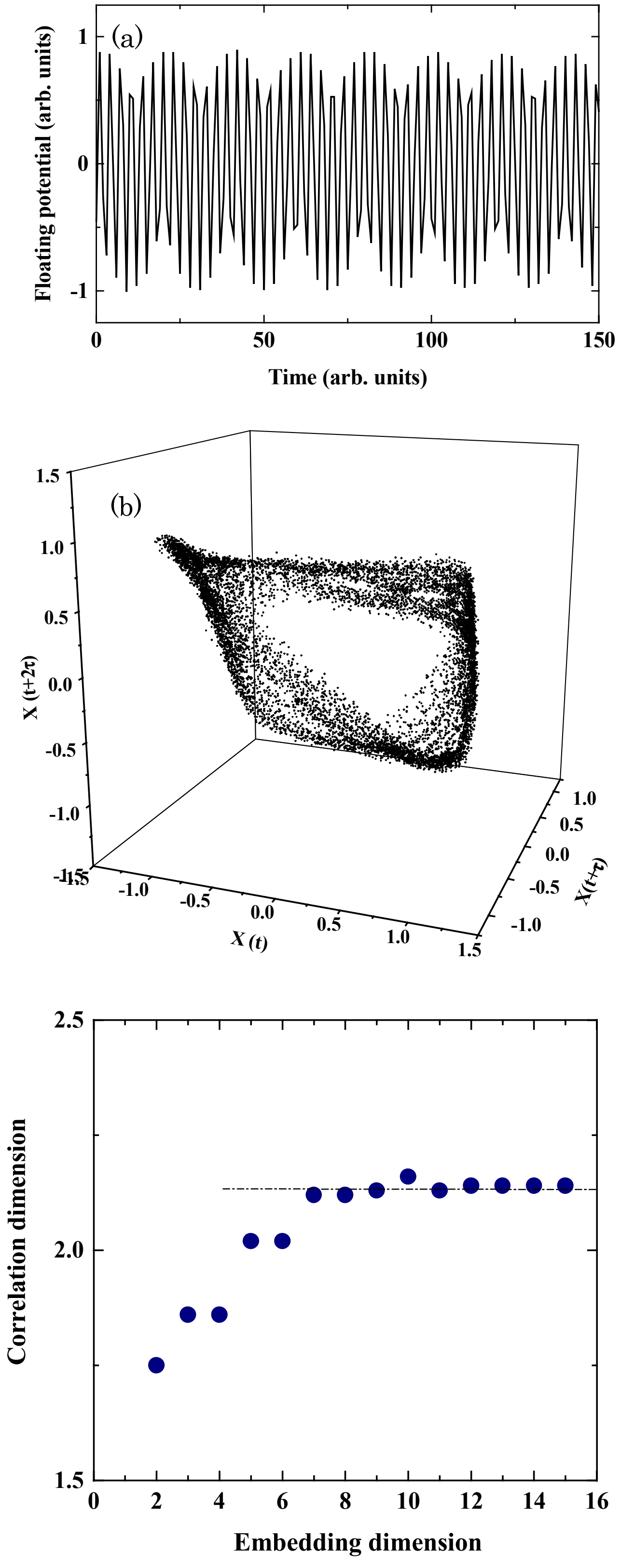

Fig. 9. Time series of floating potential, attractor of the system, and correlation dimension of the attractor of the non-periodic state shown in Fig. 7(b).

Figure 9 (a) indicates the amplitude modulation of the oscillation and non-periodic behavior of the system. The reconstructed attractor in the three dimensional phase space has the complicated shape with the folding structures. The correlation dimension of the attractor is calculated to be 2.3, non-integer. The fractal correlation dimension indicates that the system is the chaotic state. Therefore, the system would reach the chaotic state at slightly out of the resonance.

4. Conclusion

Fundamental oscillation with a frequency of f_{pe} and its higher harmonics were excited in the Pierce electron beam plasma system. Fundamental oscillation agrees well with a dispersion relation of Langmuir mode in an electron beam plasma system, while higher harmonics do not agree with the dispersion relation. The chaotic state appeared in the extended Pierce electron beam plasma system in the case of slightly out of resonance.

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